GEORGIA INSTITUTE OF TECHNOLOGY
ENGINEERING EXPERIMENT STATION
ATLANTA, GEORGIA 30332

5 August 1965

Department of the Navy
U. S. Navy Mine Defense Laboratory
Panama City, Florida

Attention: Dr. E. A. Hogge, Code 712

Subject: Monthly Progress Letter Report 1, Project A-874
"Bubble Measurement in Sea Water"
Contract No. N600 (24)-59885, Mod. No. 15
Covering the Period from June 14 to July 31, 1965

Gentlemen:

The purpose of this research is the laboratory evaluation of the Coulter Counter for determining the bubble population of sea water. The proposal dated 21 May 1965 is being followed.

A bubble generator sketched in Figure 1 has been constructed. The ultrafine glass frit filter has a specified pore size of 1.2 microns (10^{-12} meter). With 15 psi air pressure on the lower side of the frit, fairly large bubbles, up to 1 mm diameter, are generated. The 1 inch o.d. tube with flat bottom (riser) channels the flow of water across the surface of the frit, sweeping the bubbles away while the size is still small. The gap between the frit and the end of the riser is controlled by three strips of 0.0015-inch mylar film cemented radially on the lower surface of the riser.

The bubble generator is attached to the bottom of the plenum chamber shown in Figure 2. The air passes upward through the frit and the bubbles are swept into the riser by the flow of water from outside to inside of the riser. The large bubbles rise to the top of the chamber and thence to the outlet. The slower-rising, smaller bubbles drift along to the vicinity of the counting aperture.

The size of bubbles measured depends on the air pressure, the rate of flow of water across the frit and on the location of the counting aperture in the plenum chamber.

For measurements with the bubble generator, the constant displacement of fluid through the aperture plate of the Coulter Counter by suction has been replaced by a constant positive head on the outside of the aperture plate somewhat higher than the head on the inside. A count for a fixed time interval now measures a uniform volume of liquid. With a differential head of 14 inches of salt solution the 280 micron aperture currently in use passes about 4 milliliters of fluid in 30 seconds.

A Graflex camera with a 12-inch bellows is being fitted with an extension and adapter for a 48-mm Microtessar to provide a magnification of about 7 for photography of the bubbles in the plenum adjacent to the counter aperture. A General Radio Co. Strobotac type 1531 A is available for taking multiple images at one-half second intervals or faster. More light, if needed, can be obtained with the type 1532 Strobolume.

During his recent visit to the U. S. Navy Post Graduate School Dr. Bennett visited the laboratory of Dr. Herman Medwin. A program of accoustic attentuation measurements is in progress. Results of much of the work is contained in two theses: (1) Instrumentation to determine the presence and accoustic effect of microbubbles near the sea surface, by Pat D. C. Barnhouse, Michael J. Stoffel and Robert Zimdar, 1964, and (2) Accoustic detection of microbubbles and particulate matter near the sea surface, by Stanley Buxcey, James E. McNeil and Robert H. Marks, Jr., 1965.

Plans for the next month

Use of the bubble generator will be continued until a stable counting procedure is achieved and diameter measurements are reproducible. The photographic technique will then be developed for comparison measurements.

Persistent bubbles will be measured by recirculation of the water without air pressure applied to the frit so that no new bubbles are generated. By successive re-runs, the change of bubble population with time will be noted. If the persistence is long, the effects of decreased and increased pressure will be measured.

While the bubble generator is in use we can expect the water to be saturated with air. In the future measurements of stable bubbles, however, the amount of dissolved gasses may be important. The oxygen content can be readily measured with equipment available at Tech, both the Yellow Springs Instrument Company analyzer and the Precision Scientific Company's analyzer.

Respectfully submitted,

Arthur L. Bennett
Project Director

ALB:brj

GEORGIA INSTITUTE OF TECHNOLOGY

ENGINEERING EXPERIMENT STATION

ATLANTA, GEORGIA 30332

7 September 1965

Department of the Navy
U. S. Navy Mine Defense Laboratory
Panama City, Florida

Attention: Dr. E. A. Hogge, Code 710

Subject: Monthly Progress Letter Report 2, Project A-874
"Bubble Measurement in Sea Water"
Contract No. N600(24)-59885, Mod. No. 15
Covering the Period from July 31 to August 31, 1965

Gentlemen:

The purpose of this research is the laboratory evaluation of the Coulter Counter for determining the bubble population of sea water. The proposal dated 21 May 1965 is being followed.

The bubble generator described in Letter Report No. 1 gave highly variable bubble counts because of turbulence in the plenum. A glass tube 0.79 inch O.D. and about 0.67 inch I.D. was bent to a 45° curve and inserted in the riser. The upper end was cut vertically to face the counter tube with a clearance of about 0.2 inches. The flow of water was increased (4 to 5 ml/second) by increase of the head across the generator to 60 inches and by adjusting the clearance between the frit and the riser to produce a discharge speed of about 2 cm/sec from the riser extension. Relatively smooth flow around the counter aperture tube is now produced. The larger bubbles rise to the upper surface of the curved riser extension and are discharged about a centimeter above the counter aperture.

About a dozen bubble counts have been made in synthetic sea water for the various conditions, changing the water flow, the air pressure, and the counter aperture, initially 280 microns, later 100 microns. Calibrations of these apertures in the plenum with ragweed pollen of mean diameter 19.3 microns have been made with the bubble generator turned off and also in the conventional use of the Coulter Counter.

The background count of particles or persistent bubbles has been made at various times after the air supply was shut off. It is suspected that plant or animal growth or debris may be contributing to the count. Since the count of large particles was small, the 50 micron aperture was calibrated and used to measure the persistent particles to increase the accuracy. The same sample was remeasured after boiling at room temperature under vacuum for two hours.

Analysis of several counts indicates a logarithmic normal distribution of equivalent bubble diameters. This type of distribution, skewed toward larger diameters, is characteristic of particles found in nature. On the relatively rough surface of the frit where the bubbles are generated small bubbles tend to coalesce into larger ones or grow in depressions so this type of distribution is not unexpected.

A 48 mm microtessar objective was set up at a magnification of seven. When the bubble flow near the aperture was illuminated by a flash lamp at a repetition rate of 40 a second bubbles were readily seen. A more stable mount for the camera must be constructed before photographs can be taken.

The sample of Gulf water furnished by MDL was received one week after collection. A background count was made a week later for comparison with the synthetic solution at a comparable age. Bubble generation in this water has not yet been attempted because the system has to be modified to handle a smaller quantity of water.

Plans for the next month

Analysis of the available data will be made and put in form for presentation. When the equipment is ready, arrangements for additional samples of Gulf will be made.

Photographs of the bubble generator in operation will be attempted as soon as time permits.

Respectfully submitted,

Arthur L. Bennett
Project Director

ALB:brj

GEORGIA INSTITUTE OF TECHNOLOGY

ENGINEERING EXPERIMENT STATION

ATLANTA, GEORGIA 30332

5 October 1965

Department of the Navy
U. S. Navy Mine Defense Laboratory
Panama City, Florida

Attention: Dr. E. A. Hogge, Code 710

Subject: Monthly Progress Letter Report 3, Project A-874
"Bubble Measurement in Sea Water"
Contract No. N600(24)-59885, Mod. No. 15
Covering the Period from August 31 to September 30, 1965

Gentlemen:

The rebuilding of the laboratory bubble generator equipment is nearly completed. A circulating pump will be used to avoid contamination from the air and to operate with a smaller quantity of liquid. The work has gone slowly this month because of the shortage of help between Quarters.

Attention has been centered on the analysis of the data obtained earlier. The calibration procedure for the solutions in use was found to be faulty. The method has been corrected and repeatable measurements are now obtained.

The background counts of synthetic sea water and of Gulf water are submitted herewith in Figures 3 and 4 (in sequence with Letter Report No. 1). The conventional representation of the data, percent of particles larger than the size given by the abscissa, is shown in Figure 3. This reduction is based on the assumption of a log-normal particle distribution which appears reasonable. A total count must be assumed, however, and until the measurements with 50 micron aperture are available, some uncertainty in the ordinate remains.

Figure 4 presents the particle count (abscissa) vs particle diameter. These data are needed for correction of the bubble counts with the bubble generator operating. The background counts become significant relative to the bubble counts in the laboratory only below about 10 microns diameter. Since quiet sea water in situ is expected to have a lower bubble count, however, the measurement of the small particle background is of importance.

The relatively high count in the synthetic sea water (made with distilled water) is disturbing, but then the measurement was taken on the fluid which had been in use more than a month. The water was exposed to room air drawn into the flasks during transfer through the bubble generator. This source of contamination will be avoided in the rebuilt equipment.

Plans for next month

The measurements taken previously will be analysed.

The new equipment will be used for photographing bubbles under the repeatable measurement conditions in both synthetic sea water and Gulf water.

Respectfully submitted,

Arthur L. Bennett
Project Director

PARTICLE SIZE ANALYSIS
Coulter Counter

Source | Operator | Date

	material and sample number	electrolyte and dispersant	aperture	
⊙				
⊡				
△				
◇				

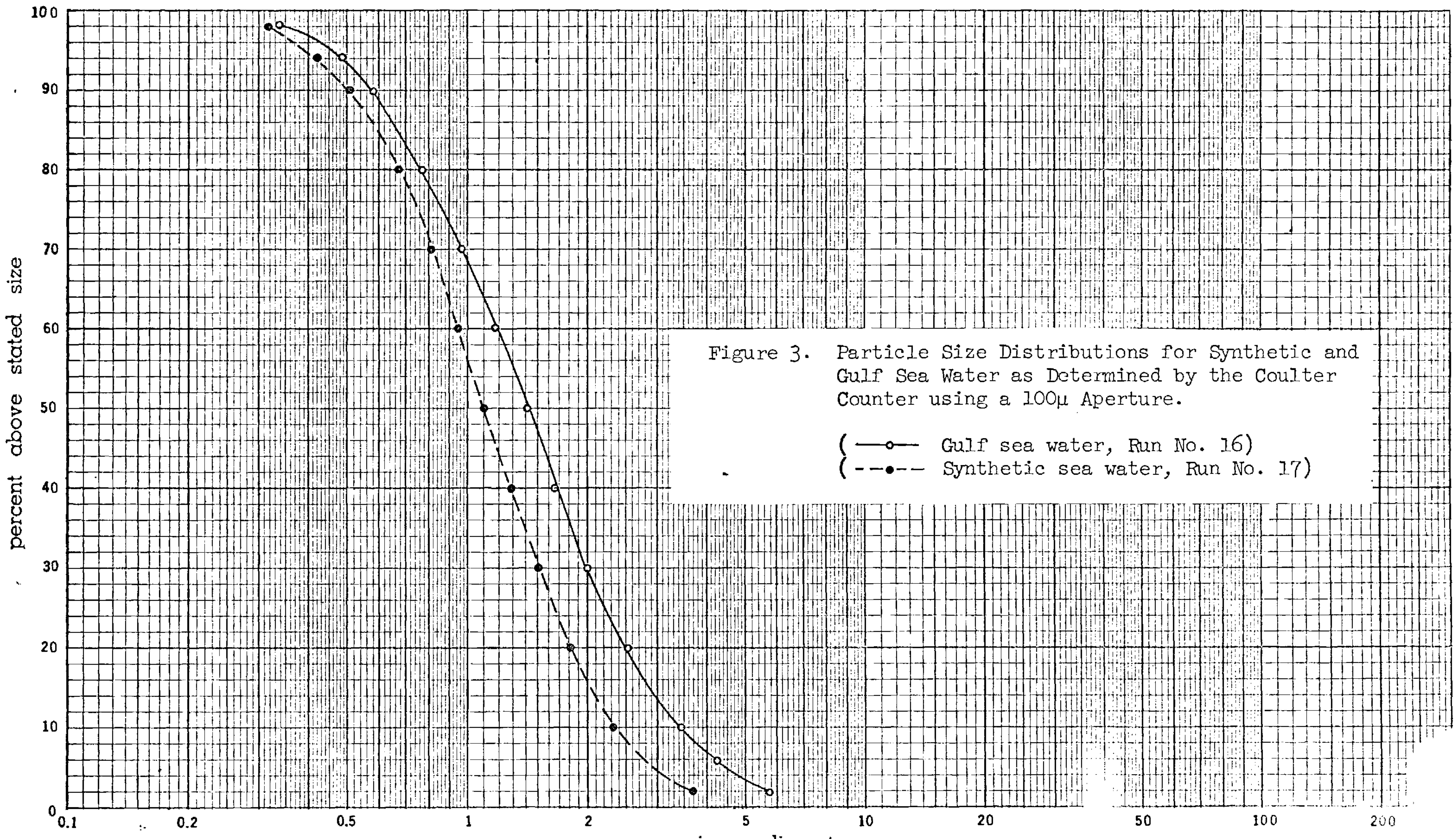

Figure 3. Particle Size Distributions for Synthetic and Gulf Sea Water as Determined by the Coulter Counter using a 100μ Aperture.

(—o— Gulf sea water, Run No. 16)
(--•-- Synthetic sea water, Run No. 17)

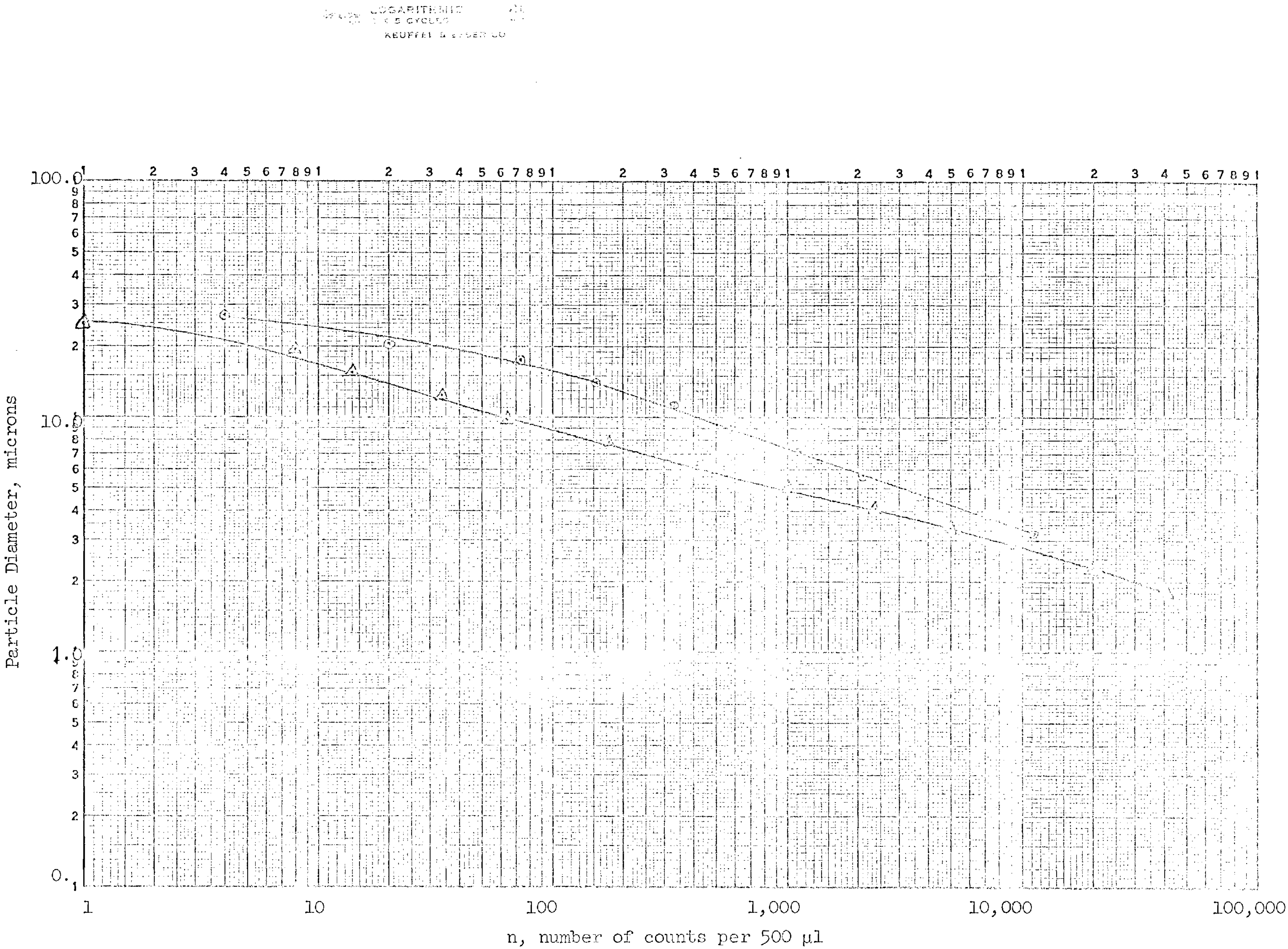

Figure 4. Background Particle Count for Synthetic and Gulf Sea Water as Determined by the Coulter Counter using a 100µ Aperture. (⊙ Run No. 16, Gulf sea H_2O, △ Run No. 17 Synthetic Sea H_2O.)

GEORGIA INSTITUTE OF TECHNOLOGY
ENGINEERING EXPERIMENT STATION
ATLANTA, GEORGIA 30332
8 November 1965

Department of the Navy
U. S. Navy Mine Defense Laboratory
Panama City, Florida

Attention: Dr. E. A. Hogge, Code 710

Subject: Monthly Progress Letter Report 4, Project A-874
"Bubble Measurement in Sea Water"
Contract No. N600(24)-59885, Mod. No. 15
Covering the Period from Oct. 1 to Oct. 31, 1965

Gentlemen:

The purpose of this research is the laboratory evaluation of the Coulter Counter for determining the bubble population of sea water. The proposal dated 21 May 1965 is being followed.

The closed-system bubble generator has been put in operation with Gulf water. Two liters are adequate for continuous operation.

The 400 micron Coulter aperture has been calibrated and used both in the conventional counter system and in the bubble generator. This aperture is useable over the equivalent particle diameter range about 5 to 150 microns.

Background counts in Gulf water de-bubbled under vacuum and measured in a beaker show 30 to 100 particles/milliliter of equivalent diameter greater than 25 microns.

Gulf water was passed through a 30 micron screen to remove the large solid particles which might plug the bubble generator. The counts in the bubble generator show about 1000 bubbles/milliliter greater than 100 microns equivalent diameter with the counting aperture near the top of the discharge from the riser tube extension. The count of 50 microns diameter and smaller is well above 10, 000 (too high to count with the present bubble generator). A run under similar conditions with a smaller aperture is needed to get a good count of the smaller bubbles. The bubble generator is currently operated with a gap of about 0. 1 mm between the frit and the flat end of the riser tube, twice the gap used previously.

Future Work

Emphasis on larger bubbles is indicated to better simulate the surf zone and to facilitate measurement by photography of bubble size for calibration of the counter.

Revision of the equipment to produce larger bubbles is planned. Photographic comparison will then be made.

Respectfully submitted,

Arthur L. Bennett
Project Director

ALB:brj

GEORGIA INSTITUTE OF TECHNOLOGY

ENGINEERING EXPERIMENT STATION

ATLANTA, GEORGIA 30332

7 December 1965

Department of the Navy
U. S. Navy Mine Defense Laboratory
Panama City, Florida

Attention: Dr. E. A. Hogge, Code 710

Subject: Monthly Progress Letter Report 5, Project A-874
"Bubble Measurement in Sea Water"
Contract No. N600(24)-59885, Mod. No. 15
Covering the Period from Nov. 1 to Nov. 30, 1965

Gentlemen:

The purpose of this research is the laboratory evaluation of the Coulter Counter for determining the bubble population of sea water. The proposal dated 21 May 1965 is being followed.

The frit in the bubble generator has been changed from U (1.2 micron pore size) to F (4 to 5 micron). From 100 to 400 bubbles/milliliter over 100-micron diameter have been measured with the 400 micron aperture; the number of large bubbles depends, as expected, on the water flow and air pressure.

Photographs have been taken with Microtessar lens at F/4.5, magnification of 8, on 35 mm film. The light source is a Strobotron Mod. 1531A. A single flash for each frame gives better resolution than multiple flashes.

Plans for Next Month

Coulter Counter apertures of smaller diameter will be used to extend the particle counts to lower sizes with the F frit in the bubble generator.

Photographic techniques will be improved.

Respectfully submitted,

Arthur L. Bennett
Project Director

ALB:ms

GEORGIA INSTITUTE OF TECHNOLOGY

ENGINEERING EXPERIMENT STATION

ATLANTA, GEORGIA 30332

4 February 1966

Department of the Navy
U. S. Navy Mine Defense Laboratory
Panama City, Florida

Attention: Dr. E. A. Hogge, Code 710

Subject: Monthly Progress Letter Report 6, Project A-874
"Bubble Measurement in Sea Water"
Contract No. N600(24)-59885, Mod. No. 15
Covering the Period from Dec 1, 1965 through Jan. 31, 1966

Gentlemen:

The frit in the bubble generator identified in Letter Report 5 was incorrectly identified as porosity F; the correct designation is M, pore size 10 to 15 microns. The M frit, even with the active area an anulus of 14 to 17 mm diameter, gave too many bubbles over 100 micron diameter at 4 psi gauge near the minimum pressure useable. In an attempt to reduce the breadth of the anulus, the filter was blocked by the epoxy coating. An intermediate frit, porosity F (pore size 4 to 5.5 microns) has therefore been prepared and installed.

During this period experimental work has lagged. Effort has been concentrated on theoretical work for inclusion in a Technical Report. The theory of bubble absorption and buoyant rise has been reviewed with a view to computations of the change in bubble size with time and with pressure. The behavior of a bubble in transiting the counter has been investigated; it is found that the bubble may be elongated a few percent, but disruptive effects are unlikely. The small deformation should produce no distortion of the measured equivalent diameter since the pulse height is primarily dependent on the equivalent volume of the particle.

No additional photographs have been taken. A General Radio Type 1539-A Stroboslave is expected to become available during February. The Stroboslave can be synchronized with the Strobotac so that bubbles can be illuminated from two sides to give more uniform images.

Plans for Next Month

A Technical Report is being prepared on the work in progress.

Measurements with the Coulter Counter will be continued and new photographic procedures applied.

Work on techniques for application of the counter under field conditions will be accelerated.

Respectfully submitted,

Arthur L. Bennett
Project Director

ALB:brj

GEORGIA INSTITUTE OF TECHNOLOGY
ENGINEERING EXPERIMENT STATION
ATLANTA, GEORGIA 30332

8 March 1966

Department of the Navy
U. S. Navy Mine Defense Laboratory
Panama City, Florida

Attention: Dr. E. A. Hogge, Code 710

Subject: Monthly Progress Letter Report 7, Project A-874
"Bubble Measurement in Sea Water"
Contract No. N600(24)-59885, Mod. No. 16
Covering the Period from Feb. 1 through Feb. 28, 1966

Gentlemen:

The use of the F frit in the bubble generator has been continued. Measurements with the 400 and 280 micron diameter apertures are consistent over the range of diameters from 160 microns to 75 microns at 7 psi air pressure and flow of 10 ml/sec through the bubble generator. The upper size limit is 40% of the 400 micron aperture. Both diameter limits are instrumental; the larger at 40% of the 400 micron aperture, the smaller apparently caused by coincidence effects at relatively high counts. A larger aperture will be used to extend the maximum size limit. The coincidence effect will be examined by reducing the total number of bubbles. The counting procedures are approaching the point where calibration by photography will be appropriate.

The search for an interpretation of the flow through the orifice and the behavior of bubbles in the accelerated flow has delayed the completion of the Technical Report. The comment by Birkhoff (Jets, Wakes, and Cavities by Garrett Birkhoff and E. H. Zarantonello, Academic, 1957) on the acceleration of bubbles relative to the accelerated flow around them is stimulating but without clue to the experimental or theoretical basis.

During the month a number of water samples were analyzed. The results are given in a special report under this project.

Respectfully submitted,

Arthur L. Bennett
Project Director

ALB:ms

GEORGIA INSTITUTE OF TECHNOLOGY
ENGINEERING EXPERIMENT STATION
ATLANTA, GEORGIA 30332

5 April 1966

Department of the Navy
U. S. Navy Mine Defense Laboratory
Panama City, Florida

Attention: Dr. E. A. Hogge, Code 710

Subject: Monthly Progress Letter Report 8, Project A-874
"Bubble Measurement in Sea Water"
Contract No. N600(24)-59885, Mod. No. 16
Covering the Period from March 1 through March 31, 1966

Gentlemen:

Calibrations of the apertures 560, 400, and 280 microns were made with pecan pollen, diameter 48 microns. The calibration of the 280 micron aperture differs about 9% from the previous calibration with ragweed pollen (19 microns). The previous inconsistency of bubble runs with the apertures 560 and 280 is much reduced. The change appears to be in the gain adjustment of the Counter, but further measurements are needed to establish the relation between the bubble diameter and measurements with different apertures.

The Mine Defense Laboratory was visited on March 11 for another purpose; a short discussion of the project and related problems with the technical staff was helpful.

Mr. Dowling and the undersigned met at the Naval Research Laboratory on March 24 with Mr. Hiller, Mr. Mathes, and Mr. Ricalzone who are working on particle and bubble measurement. Mr. Nefebov added pertinent comments on related topics. The NRL group is deeply involved in both research and instrument development in this area. The exchange of experience was most helpful and stimulating.

On March 25 the two of us and Mr. Hiller visited Mr. W. R. Turner at Vitro Research Laboratories. In addition to the acoustic microbubble spectrum analyzer which Mr. Turner's group is developing for BuShips, they continue active in the study of the physics of bubbles. This discussion was somewhat more on acoustic problems, but most pertinent to the area of mutual interest. Mr. Turner continues to be most cooperative in freely exchanging his extensive experience in this work.

The two meetings indicated that the efforts of all four activities participating are well coordinated and mutually supplementary.

Respectfully submitted,

Arthur L. Bennett
Project Director

ALB/jw

GEORGIA INSTITUTE OF TECHNOLOGY

ENGINEERING EXPERIMENT STATION

ATLANTA, GEORGIA 30332

4 May 1966

Department of the Navy
U. S. Navy Mine Defense Laboratory
Panama City, Florida

Attention: Dr. E. A. Hogge, Code 710

Subject: Monthly Progress Letter Report 9, Project A-874
"Bubble Measurement in Sea Water"
Contract No. N600(24)-59885, Mod. No. 16
Covering the Period from April 1 through April 30, 1966

Gentlemen:

For the larger apertures currently in use, the Coulter 560 μ diameter and a rounded orifice blown in glass of 0.7 mm diameter measured pollen was not available. Several hundred counts under varied conditions have been made of corn pollen of approximately 90 μ average diameter. Calibrations and further measurements of bubbles with these apertures have been made.

Calibration of the Coulter Counter electronics has been checked with a pulse generator attenuated to supply signals. No appreciable deviation from nominal calibration was found.

Additional measurements of bubbles with photographic coverage is expected to complete the experimental work planned.

Respectfully submitted,

Arthur L. Bennett
Project Director

ALB:brj

GEORGIA INSTITUTE OF TECHNOLOGY
ENGINEERING EXPERIMENT STATION
ATLANTA, GEORGIA 30332

3 June 1966

Department of the Navy
U. S. Navy Mine Defense Laboratory
Panama City, Florida

Attention: Dr. E. A. Hogge, Code 710

Subject: Monthly Progress Letter Report 10, Project A-874
"Bubble Measurement in Sea Water"
Contract No. N600(24)-59885, Mod. No. 16
Covering the Period from May 1 through May 31, 1966

Gentlemen:

Calibration of apertures 280, 400, 560 μ and 0.7 mm with corn pollen were completed. Gulf water was then filtered and nine runs were made with the above series of apertures. The bubble generator with a small exposed area of F-frit was operated at low air pressure, 7 to 5 psi gauge, to determine the performance of the counter with reduced size and number of bubbles.

Six runs were made as control of the bubble counts while photographs of the bubbles were taken. The second Strobotac used for illumination at 180° from the first (both at 90° from the camera axis) was inoperative at high intensity and proved inadequate. The beam of one Strobotac was then collimated with a lens and the beam reflected back into the plenum. This arrangement gave fairly good dual highlights on the bubble images, but was deficient on the second run because of difficulty in alignment of the optics.

Analysis of the measurements and preparation of the data for a final report is progressing.

Respectfully submitted,

Arthur L. Bennett
Project Director

ALB:brj

GEORGIA INSTITUTE OF TECHNOLOGY
ENGINEERING EXPERIMENT STATION
ATLANTA, GEORGIA 30332

4 August 1966

Department of the Navy
U. S. Navy Mine Defense Laboratory
Panama City, Florida

Attention: Dr. E. A. Hogge, Code 710

Subject: Monthly Progress Letter Report 11, Project A-874
"Bubble Measurement in Sea Water"
Contract No. N600(24)-59885, Mod. No. 16
Covering the Period from June 1 through July 31, 1966

Gentlemen:

The response of the Coulter Counter Model A electronics have been checked with an oscilloscope. Part of the difficulty in counting is found to be the inadequate low frequency response of the preamp; the response to small particle counts is blanketed by the slow recovery from large pulses.

The way is now clear to interpret the measurements. The reduction is well along and some photographs have been measured. The planned lighting has been successful with two lamps at 180° from each other in a plane perpendicular to the camera axis. The highlights are measured, rather than the outline of the bubble.

Work is progressing on the technical report.

Respectfully submitted,

Arthur L. Bennett
Project Director

ALB:brj

GEORGIA INSTITUTE OF TECHNOLOGY
ENGINEERING EXPERIMENT STATION
ATLANTA, GEORGIA 30332

February 25, 1966

Department of the Navy
U. S. Navy Mine Defense Laboratory
Panama City, Florida

Attention: Dr. E. A. Hogge, Code 710

Subject: Special Letter Report
Project A-874
"Particulate Matter in Water"
Contract No. N600(24)-59885, Mod. No. 16

Pursuant to the visit on 14 January 1966 of Dr. Ernest Hogge and Mr. Jerry Pike, an investigation of the chlorinity and the particulate content of samples of water were undertaken.

The chloride ion content and pH were measured under the supervision of Dr. R. S. Ingols, Research Professor of Applied Biology, by the mercury nitrate procedure (12th Edition, Standard Method for Analysis of Water and Waste Water, American Public Health Association, 1965). The chloride measurements (in mg/liter) have been converted to chlorinity and salinity without correction for the density in Table 1. The computed salinity = 0.03 + 1.805 (chloride ion/liter).

TABLE I

SALINITY AND pH

Sample no.	Cl- mg/ℓ	Approx chlorinity	Approx salinity	pH
137	7180	7.2%	13.0%	8.2
138	6850	6.9	12.4	8.6
1090	8850	8.9	15.5	8.4
1091	7500	7.5	13.6	8.8
1092	6550	6.5	11.9	8.4
1093	5860	5.9	10.6	8.9
1095	7500	7.5	13.6	8.1
1096	2240	2.2	4.1	8.8
1190	3200	3.1	5.8	8.8
1191	2350	2.2	4.3	7.6

Dr. Charles E. Weaver, Professor of Ceramics Engineering, examined the sediment of three samples with the following comments:

> No. 1092. Sediment approximately 30% quartz, 50% illite, 20% kaolinite, and trace of feldspar.
> No. 1090. Similar to 1092 but with minor amount of montmorillonite.
> No. 1096 and No. 1190. X-ray analysis showed nothing. Microscopic examination indicated a thin amorphous film on the filter with small crystalline needles imbedded.

Because of the special interest of the sponsor in the sediment, further tests were made by Mr. James Neiheisel, graduate student in Ceramics Engineering.

The solid matter in the MDL No. 1191 water appears to be minute zeolite crystals (thomsonite) in an amorphous isotropic clear colorless substance, Fig. 1(a). The amorphous substance comprises about 90% of the material; index immersion techniques reveal an index of refraction of about 1.480 to 1.500. The anisotropic minerals are radiated fibrous crystals which occur immeshed in the amorphous isotropic material, Fig. 1(b,c). Index range of 1.530 to 1.545 is based on relief characteristics rather than true Becke Line since isolated grains do not exist. The mineral is believed to be thomsonite, a zeolite variety.

Treatment with HCl causes the mineral matter to disappear or become amorphous, Fig. 2(a). This behavior is characteristic of zeolites; the amorphous material has an index of about 1.50. Treatment with H_2SO_4 results in strong effloresence and a resulting clear liquid, suggesting an inorganic complex.

While the exact nature of the amorphous mineral substance is in doubt, it is noted that if placed on glass and allowed to evaporate to dryness, elongate-prismatic crystals of low bi-refringence (low luster) tend to form in the amorphous material which are larger and more homogeneous than the acicular crystals; these are length-fast and of very low bi-refringence. Some spherical crystals, which display uniaxial interference figure with reaction for (+) sign, are seen in Fig. 2(b). These crystals may be quartz.

Particle size distribution was analyzed under the direction of Dr. John H. Burson, III, Senior Research Engineer.

Particle size distributions on a volume basis for samples 1092 and 1093 are presented in Figs. 3 and 4. The size distributions were determined with a Model A Industrial Coulter Counter. The operation of the Counter is described in Technical Report Number 1 of this project. Both size distributions were determined by a double aperture analysis technique which permits a more detailed examination of both the large and small ends of the size distribution.

The particulate matter in both samples was in a highly flocculated state when received and, for the most part, had settled to the bottom of the sample containers. De-flocculation and re-dispersion of the particulate matter was accomplished by subjecting the samples in the original containers to an intense ultrasonic field for about five minutes. A sample of this material was then withdrawn from the containers and diluted approximately 1000:1 with filtered, one per cent sodium chloride electrolyte. This dilute solution was again subjected to a five minute ultrasonic treatment prior to analysis on the Coulter Counter. During size distribution analysis, the samples were stirred slowly with a glass marine-type propellor to retard re-flocculation.

Particle size distributions on a particle number basis for samples 1092 and 1093 are presented in Table II. Comparison of these data with the size distributions of Figs. 3 and 4 shows that the number-mean-diameters for both samples are considerably smaller than the volume-mean-diameters. This is a result of the very small number percentage of larger particles present in both samples and the disproportionate contribution they make to the specific sample volume.

Particle concentration data as a function of particle diameter are presented in Table IV for samples 1092 and 1093. These data are for the un-diluted materials, that is, the concentration just as they came from the sample bottles after five minutes ultrasonic treatment.

Pycnometer measurements of the unfiltered and filtered water showed no measurable density difference within the accuracy of measurement, about $1 \cdot 10^{-4}$.

Respectfully submitted,

Arthur L. Bennett
Project Director

Attached: 2 Tables
4 Figures

TABLE II

NUMBER CONCENTRATION OF SAMPLES

Equivalent spherical particle diameter, microns	Number of particles larger than stated size in 500 microliters	
	No. 1092	No. 1093
0.1	2.8×10^9	1.6×10^8
0.2	1.9×10^9	8.9×10^7
0.4	5.9×10^8	3.8×10^7
0.57	3.1×10^8	2.1×10^7
0.69	1.7×10^8	1.5×10^7
0.77	1.1×10^8	1.1×10^7
0.87	7.7×10^7	8.8×10^6
1.09	4.1×10^7	6.0×10^6
1.35	2.2×10^7	3.7×10^6
1.69	1.1×10^7	2.1×10^6
2.15	5.9×10^6	1.2×10^6
2.8	3.3×10^6	3.7×10^5
3.2	1.8×10^6	1.3×10^5
3.6	1.1×10^6	6.4×10^4
4.7	4.8×10^5	2.7×10^4
5.6	2.1×10^5	7.6×10^3
7.0	8.4×10^4	2.9×10^3
8.4	2.7×10^4	1.3×10^3
11.0	1.3×10^4	4.5×10^2
14.0	5.4×10^3	2.0×10^2
17.5	1.8×10^3	1.0×10^2
22.0	3.0×10^2	——

TABLE III

SIZE DISTRIBUTION OF SAMPLES

Equivalent spherical particle diameter, microns	Number percentage larger than stated size No. 1092	No. 1093
0.1	92.5	61.5
0.2	64.0	35.5
0.3	39.0	22.5
0.5	14.0	11.0
0.7	5.3	5.5
1.0	1.6	2.25
1.5	0.55	1.10
2.0	0.25	0.55
3.0	0.08	0.20
5.0	0.013	0.035
7.0	0.003	0.006
10.0	0.0007	0.0012
15.0	0.00013	0.00020
20.0	0.00003	0.00008
25.0	——	0.00004

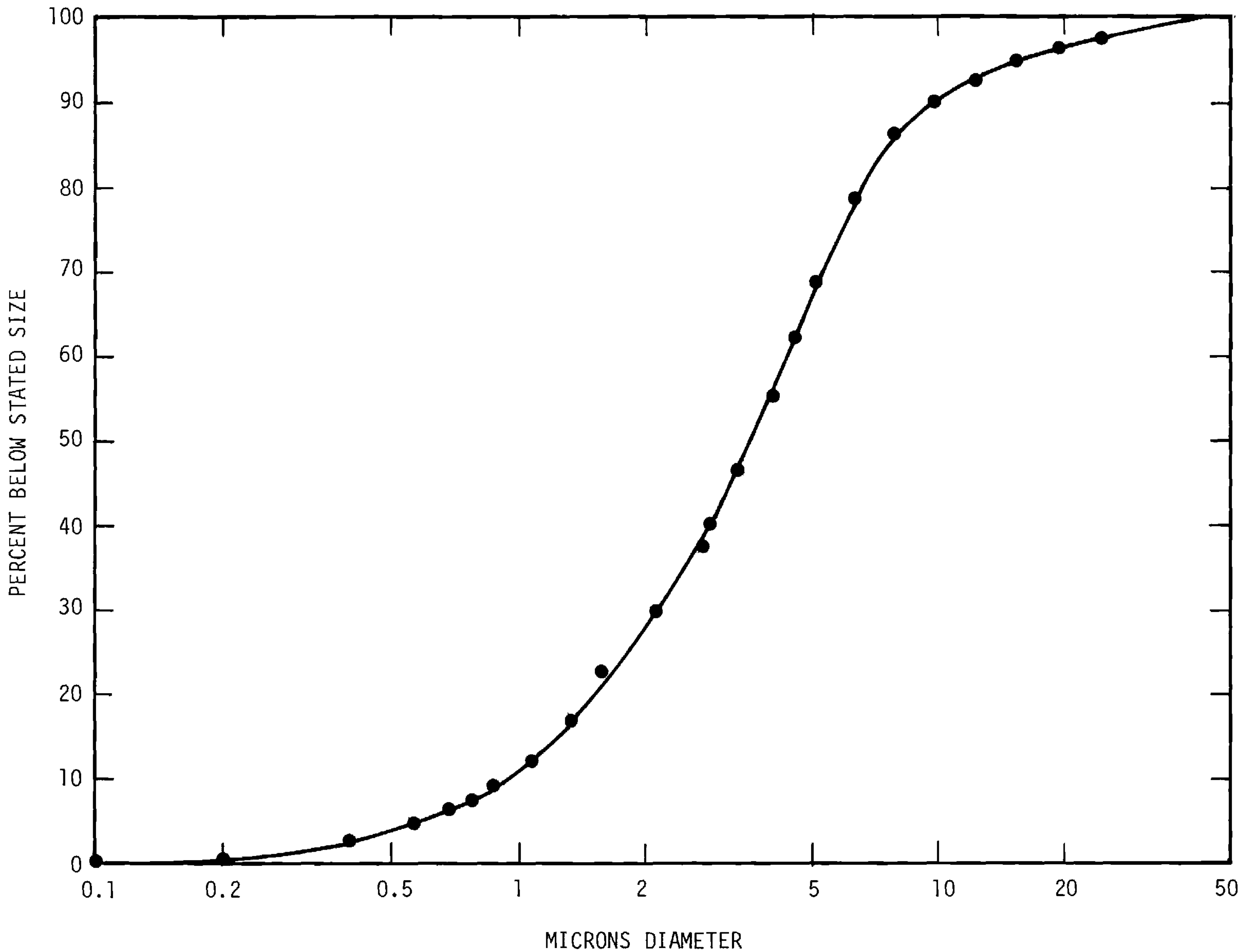

Figure 3. MDL No. 1092. Volume distribution, percent below diameter indicated by abscissa. Apertures 100 and 30 microns. Diluent 1 percent $NaC\ell$.

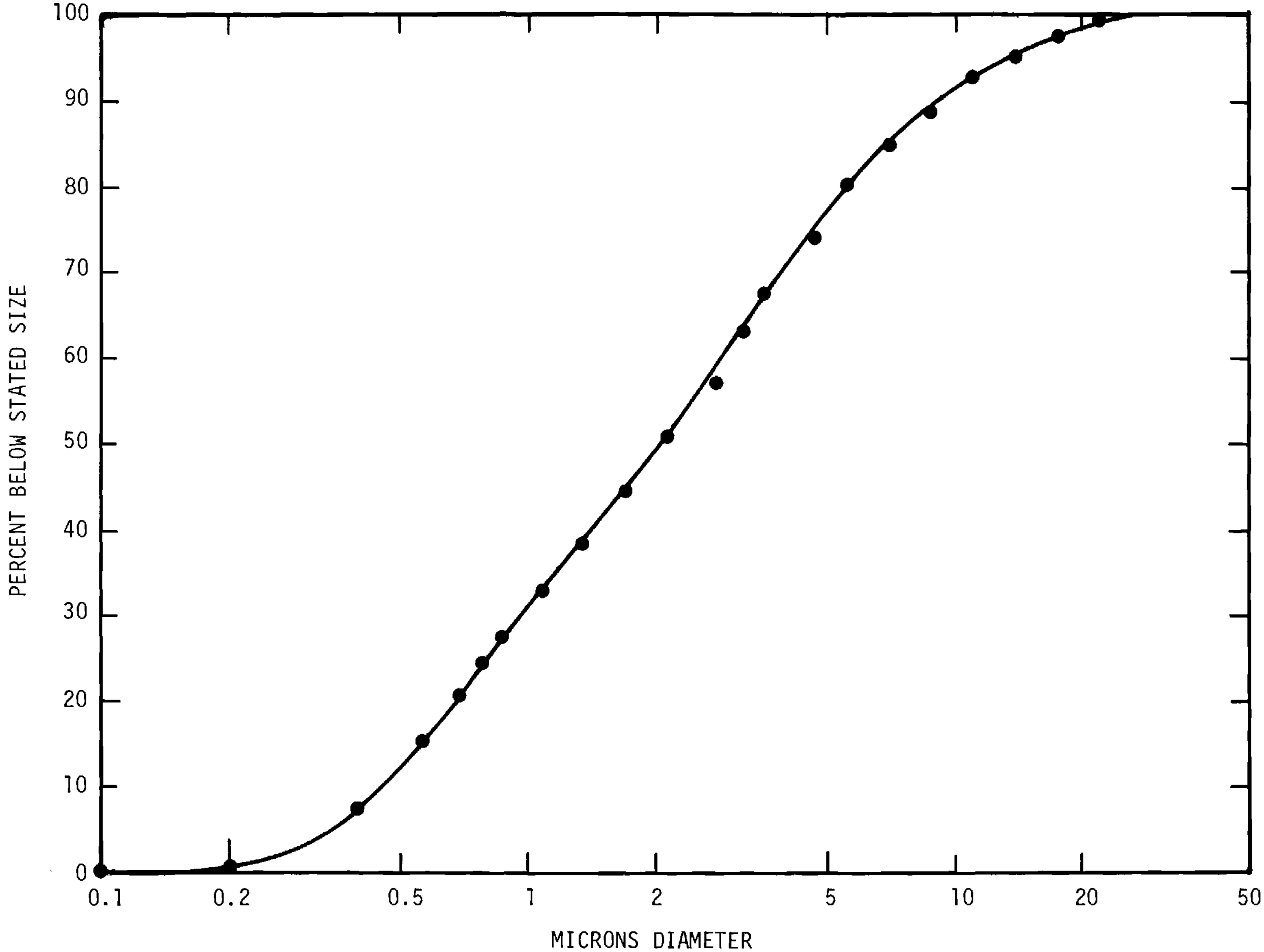

Figure 4. MDL No. 1093. Volume distribution, percent below diameter indicated by abscissa. Apertures 140 and 30 microns. Diluent 1 percent NaCℓ.

FINAL REPORT

Project A-874

BUBBLE MEASUREMENT IN SEA WATER

Arthur L. Bennett

Contract N600(24)-59885
Modifications Nos. 15 and 16

March 1970

1970

Engineering Experiment Station
GEORGIA INSTITUTE OF TECHNOLOGY
Atlanta, Georgia

Prepared for
Navy Ship Research and Development Laboratories
Panama City, Florida

Georgia Institute of Technology
Engineering Experiment Station
Atlanta, Georgia 30332

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TABLE OF CONTENTS

I. INTRODUCTION

The purpose of this investigation is the evaluation of the Coulter Counter for determining the bubble population of sea water.

The acoustic properties of sea water are of continuing interest to the US Navy because of the generally high transparency of the water compared to electromagnetic radiation. There are areas, however, such as wakes, the upper layers in the presence of waves, and the surf zone, where bubbles may strongly influence propagation.

II. BACKGROUND

The influence of bubbles on the transmission of sound in sea water was first investigated by Willis[1]. Not only is the target area many times the dimension of the bubbles, but the attentuation is also high[2]. Additional data and analysis are provided in "Propagation of Sound Through a Liquid Containing Bubbles" by Carstensen and Foldy[3], and by Fox, Curley, and Larson[4]. Acoustical measurements of tap water over the frequency range 10^5 to 10^6 kc/sec are given by Iyengar and Richardson[5].

The generation of bubbles by wave action has been investigated by Glotov, Kolobaev, and Neuimin[6]. This paper describes a bubble catcher for the photographic measurement of bubbles. The contribution of bubbles near the surface to the propagation of sound at grazing incidence was investigated by Clay and Medwin[7].

A. Bubble behavior

Liebermann[8] has described the evanescent character of bubbles. Two dissipative effects are operative, the rise of the bubble toward the surface because of its buoyancy, and its absorption by diffusion of the gas into solution in the water. Liebermann shows, for bubbles <100 microns radius (1 micron = 10^{-6} meter), that the Stokes relation for the velocity of rise, v,

$$v = (2/9)\ g\ R^2 (\rho - \rho')/\eta$$

is valid, where g is the acceleration of gravity, R the bubble radius,

$(\rho - \rho')$ the difference in densities of the bubble and the surrounding liquid, and η the viscosity. It should be noted that the gas density is dependent on the depth as well as temperature, even though it can usually be neglected entirely. For small bubbles, surface tension contributes substantially to the internal pressure, e.g., 1.4 atmosphere at a radius of one micron.

The dissipation of the gas of the bubble by solution in the surrounding liquid as controlled by the gas concentration in the liquid was formulated by Liebermann in the approximate relation,

$$R^2 = R_o^2 - 2\kappa/\rho \; (C_s - C_o)t$$

where R is the bubble radius at time t, R_o the radius at t = 0, κ the coefficient of diffusion, ρ the density of the liquid, C_s the gas concentration at saturation, and C_o the concentration in the liquid remote from the bubble.

The slight departure from linearity in the R^2 dependence on the time in the experimental measures may be accounted for by the contamination of the bubble surface. Liebermann postulates a film of thickness ΔR with another diffusion coefficient κ_1. The relation then becomes

$$R^2 = R_o^2 - (2\kappa/\rho) \; (C_s - C_o)t + (2\kappa\Delta R/\kappa_1) \; (R_o - R).$$

The value of $\kappa\Delta R/\kappa_1$ derived from the best fit is about 0.06. The coefficient of diffusion of a freely rising bubble (about twice that of a stationary bubble) was found to be about 6.25×10^{-5} at 25°C.

Turner[9] uses the expression for the change in radius due to absorption in terms of the partial pressure of the gas dissolved in the liquid, P_p, and the hydrostatic pressure, P_o;

$$\frac{(\partial(R/R_o)}{\partial t} = -\frac{x\alpha}{R_o^2} \cdot \frac{P_o + 2/R - P_p}{P_o + (4\sigma/3R_o)}$$

where x is the diffusivity constant, α the solubility constant, and σ the surface tension between the liquid and the gas. This expression is derived on the implicit assumption that there is no film or skin at the bubble surface; that is, the partial pressure of the gas in the water is maintained at the bubble surface. Stokes law is used for the rise velocity.

Turner[9] has computed the behavior of bubbles in filtered tap water saturated with air. In his Fig. 2 the change in size and height of rise of bubbles from 10- to 100-microns initial radius released at a depth of 1.37 meters in water saturated with air is shown as a function of time after bubble formation. A critical initial bubble radius of 60 microns is evident for this depth of release. Bubbles of radius 60 microns or less will be absorbed before they reach the surface, the rise increasing with the initial radius. Bubbles larger than 60 microns initial radius will reach the surface; the loss in radius decreases with the size because of the higher velocity of rise and the lower ratio of surface to volume. In water less than saturated, solution would be more rapid.

B. Bubble measurements

Even though the current interest in bubbles centers on acoustic reflection and absorption, these effects must be interpreted by independent measurements of the physical properties of the medium. Gross foreign bodies in the water, such as fish and other sizeable objects are not under consideration, but only solids or bubbles in the millimeter to micron range of the order of a tenth of an acoustic wave length.

Solid particles small relative to the wave length are generally assumed to have negligible effect on the transmission of sound except for a small amount of Rayleigh scattering. Preliminary results of measurement of volume back-scattering strength at 19.5 kHz and particle counts from 0.7 to 70 microns diameter in the vicinity of Key West have been reported by NRL[10]. The log of the particle count measured at 100-foot intervals in depth follows the volume scattering strength (db), including a rough agreement of the maximum count at 750-foot depth with the deep scattering layer peak at 600-foot depth. The acoustic back-scattering, however, was found to follow a first power variation with depth in the shallower layers, rather than the fourth power expected for Rayleigh scattering. The particle counts may, therefore, indicate small organisms. The size of the acoustic effect implies either gas bubbles in the animals or attached to them[11,12].

Bubble measurement at Georgia Tech concerns the evaluation of the Coulter Counter as a means of measurement of bubbles in sea water. Other commercial devices, such as the HIAC Counter which depends on the absorption or scattering of light by suspended particles, appear to offer no advantage over the Coulter Counter and would pose a comparable problem of calibration for counting bubbles.

C. The Coulter Counter

The industrial Model A of this equipment measures an equivalent volume of a particle which has an electrical resistivity which is high relative to the resistivity of the electrolyte serving as suspension. Most particles including finely divided metal show a resistance high enough to qualify. A large range of equivalent particle diameters can be measured by the successive use of apertures of increasing size. Apertures are made ranging in diameter from 11 microns to 2000 microns. Reliable counts are obtained for a given aperture over the diameter range from 2% to 40% of the aperture diameter.

A DC potential of 300 volts with one or more of a set of resistors in series is placed across platinum electrodes in the electrolyte, one on each side of the aperture.

The I-setting (which selects the series resistance) determines the current through the aperture, hence the voltage (or height) of the pulse corresponding to a particle of a certain size passing through the aperture. The ten steps of the I-switch each increase the current in steps of $\sqrt{2}$. As particles are drawn through the aperture by the flow of electrolyte, pulses are produced in the current. The voltage drop across the series resistor is amplified and presented on a cathode-ray tube for monitoring the operation. The CR presentation shows the pulses brightened above the level corresponding to the threshold setting. A pulse amplifier delivers the pulses above threshold to a counter. The first three decades are high-speed neon lights; four higher decades are counted on a mechanical register. The gain of the amplifier is controlled by a Gain switch with six steps, each step increasing the gain by $\sqrt{2}$. The amplified pulses are also fed to a linear voltage divider operated by the Threshold dial, calibrated in percentage, 0 to 100.

The Threshold setting, by eliminating pulses less than the corresponding height, provides an independent setting of sensitivity and establishes the lower limit of the pulse height counted.

In the use of the Coulter Counter bench-stand a measured quantity, 50, 500, or 2000 microliters is passed through the aperture for a count. The flow is drawn through the aperture by the release of mercury from a reservoir with about 15 cm head. Contacts in a horizontal section of tubing control the start and end of the counting period corresponding to the volume selected. The counter can also be used with an external timer with constant flow through the aperture; this alternative was used with the bubble generator described later.

Each aperture is calibrated by a dispersion of particles of fairly uniform size in the electrolyte in use. With sea water, the particulate matter was removed with a 0.45 micron filter and the calibrating particles added. The size distribution of the standard was determined by measurement with the microscope. The larger particles (in the range 20 to 100 microns) are usually pollen. Latex suspensions are available for small particle calibration.

1. The aperture

The flow pattern through the Coulter Counter aperture and the effect of the flow on entrained bubbles must be evaluated before the counter can be used with confidence for the measurement of bubbles. Examination of several apertures confirms the statement of the local representative that the thickness of the sapphire plate in which the round hole is drilled is three-fourths the diameter of the hole. The edges of the orifice are slightly chipped. The volume coefficients for the hydraulic head in use, 55 cm of water, are 0.80 and 0.77 for the 400 and 280 micron apertures, respectively. For the velocity corresponding to the head, 330 cm/sec, the Reynolds numbers are 1350 and 940, respectively. It is unlikely that turbulence is appreciable within any of the apertures because of the short length.

A search has not established the details of the flow in a (nearly) sharp orifice entering a short flooded tube. Since the Coulter Counter is known to give reliable measurements for particles 40% to, at most, 50% of the diameter of the aperture, the flow pattern in the tube appears not to be restrictive on the use.

The operating pressure at the entrance of the aperture was a maximum of 90 cm of water and 35 cm at the exit in the present equipment. At Atlanta the average atmospheric pressure corresponds to 1000 cm of water. The static expansion of the bubble due to the pressure decrease from 1090 cm absolute head to 1035 cm is 5% in volume or 1.5% in radius.

The distortion of the bubble by the acceleration of the fluid may be important. Birkhoff and Zarantonello[13] state that a bubble in an accelerated liquid accelerates two or three times as fast as the surrounding liquid. Under Helmholtz instability an equatorial bulge, transverse to the direction of acceleration, then occurs and later the bubble "dishes", that is, the following surface becomes concave. Although none of the circumstances of the above observation are stated, it would be appropriate for bubbles of centimeter size. As Birkhoff notes, surface tension becomes important in bubbles under 2 mm and provides an important stabilizing influence.

The change of resistance of the Coulter Counter aperture for a [14] cylinder particle with the axis in the flow direction has been analyzed under the following assumptions:

a) the aperture contents form a cylindrical resistor in which current density is uniform,

b) multiplying the aperture length by an appropriate factor covers the electrically effective zones outside the aperture,

c) the passages of individual particles occur at random and are evenly distributed through the aperture cross-section,

d) the electrically effective volume of a particle in the aperture may be expressed as a cylinder having the same resistivity as the particle. Measurements indicate that most materials respond as insulators, including copper, aluminum, and silver.

Let the particle cylinder be a·d in length and b·d in diameter, where d is the diameter of a sphere having the same volume as the cylinder. This d is thus the particle dimension as measured electrically (not necessarily the same as the physical dimension).

Now consider the aperture as having a disc segment (containing a given particle) of a diameter D equal to that of the aperture and a thickness a·d equal to the length of the particle-cylinder. Let ρ_o and ρ be the resistivities of the liquid and the particle, respectively. Then, the disc segment resistance without the particle is:

$$R_o = \rho_o \frac{a \cdot d}{(\pi/4)D^2}$$

and the resistance with the particle is that of two resistors in parallel, or:

$$R = \cfrac{1}{\cfrac{1}{\rho_o \dfrac{a \cdot d}{(\pi/4)(D^2 - b^2 d^2)}} + \cfrac{1}{\rho \dfrac{a \cdot d}{(\pi/4) b^2 d^2}}}$$

Thus, the resistance change caused by the particle is:

$$\Delta R = R - R_o = \cfrac{1}{\cfrac{(\pi/4)(D^2 - b^2 d^2)}{\rho_o ad} + \cfrac{(\pi/4) b^2 d \, \rho_o}{\rho \, a \, \rho_o}} - \frac{\rho_o ad}{(\pi/4) D^2}$$

simplified:

$$= \frac{\rho_o a}{(\pi/4) D^4} \cdot \frac{d^3 (1 - \rho_o/\rho)}{\frac{1}{b^2} - \frac{d^2}{D^2}(1 - \rho_o/\rho)} \cdot$$

But, for an equivalent sphere and cylinder of equal volume:

$$(1/b^2) = 1.5a$$

Thus,

$$\Delta R = \frac{4\rho_o}{\pi D^4} \cdot \frac{d^3}{\frac{1.5}{1 - \rho_o/\rho} - \frac{d^2}{aD^2}}$$

Response is thus directly proportional to particle volume, except as modified by the last term in the denominator. This effect is limited because d/D should not exceed a maximum of about 0.5. In practice, deviation from volumetric response has proven to be negligible for aqueous electrolytes and relatively insulating particles, due to these probable compensating factors:

a) a larger particle makes a greater increase in the current density and hence electrical heating in the rest of the aperture, thus momentarily lowering the resistivity of the electrolyte and the response to particle passage,

b) the factor a is probably somewhat greater than unity especially for larger particles which are the more likely to have irregular shapes and thus become "feathered" to align with the flow stream.

Thus, ignoring the last term in the denominator, the response equation becomes:

$$\Delta R = \frac{4d^3}{1.5\pi D^4}\rho_o(1 - \rho_o/\rho) = A\,\rho_o(1 - \rho_o/\rho).$$

Differentiating the setting equal to zero for maximum response:

$$\frac{d(\Delta R)}{d\rho_o} = A - 2A\,\rho_o/\rho = 0, \quad \text{and} \quad \rho_o = \rho/2.$$

Usually, it will be impractical to achieve this "best" resistivity ratio of 2:1, as the required fluid resistivity for many particulate materials will be too high to permit the required current in the aperture without excessive resistive noise, heating of the aperture contents, or both. Adequate pulse height is readily achieved, however, so this is of little concern.

This analysis indicates that a bubble elongated in the direction of flow will give no appreciable error for an oblate spheroid with difference in radii as much as, say, 20%. The flattening in the transverse direction (as indicated by Birkhoff et al.) occurs only when the pressure builds up beyond the orifice. Ivany et al.[15] have examined vapor cavities in a two-dimensional venturi under much more severe conditions.

For the 400 micron aperture, the transit time at 330 cm/sec is 90 microseconds; because of the symmetry, the transit time is proportional to the diameter of the aperture at constant head.

III. EXPERIMENTAL

A. Equipment

1. Bubble generator

A bubble generator sketched in Figure 1 was constructed. The ultra-fine glass frit filter has a specified pore size of 1.2 microns. With 15 psi air pressure on the lower side of the frit, fairly large bubbles, up to 1 mm diameter, are generated. The 1-inch o.d. tube with flat bottom (riser) channels the flow of water across the surface of the frit, sweeping the bubbles away while the size is still small. The gap between the frit and the end of the riser is controlled by three narrow strips of 0.0015-inch mylar film cemented radially on the lower surface of the riser.

The bubble generator is attached to the bottom of the plenum chamber shown in Figure 2. The air passes upward through the frit and the bubbles are swept into the riser by the flow of water from outside to inside of the riser. The large bubbles rise to the top of the chamber and thence to the outlet. The slower-rising, smaller bubbles drift along to the vicinity of the counting aperture.

This bubble generator gave highly variable bubble counts because of turbulence in the plenum. A glass tube 0.79-inch O.D. and about 0.67-inch I.D. was bent to a 45° curve and inserted in the riser. The upper end was cut vertically to face the counter tube, with a clearance of about 0.2 inches. The flow of water was increased to 10 ml/second by increase of the head across the generator and by adjusting the clearance between the frit and the riser to produce a discharge speed of about 5 cm/sec from the riser extension. Relatively smooth flow around the counter aperture tube was produced. The larger bubbles rise to the upper

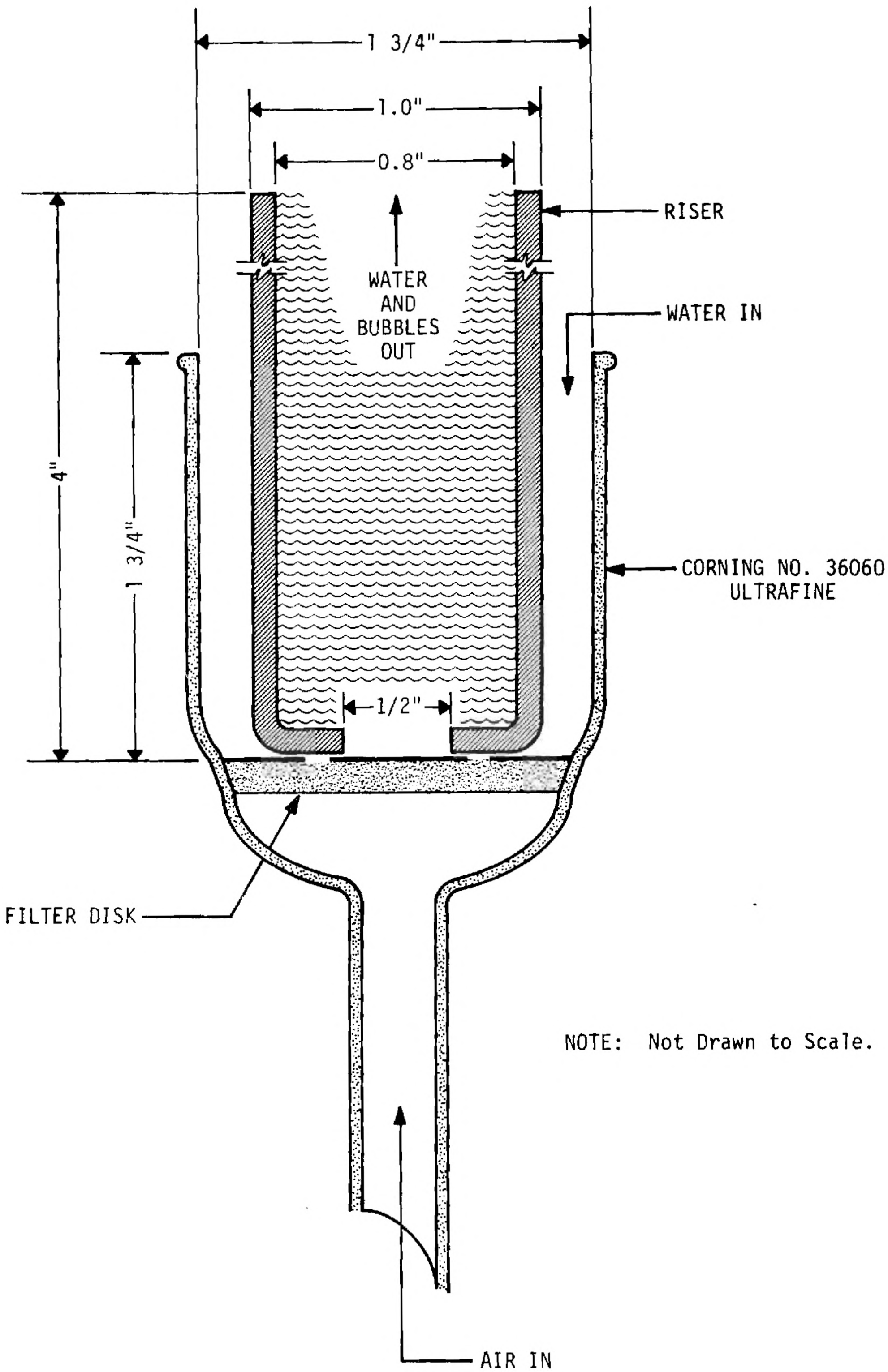

Figure 1. Bubble Generator.

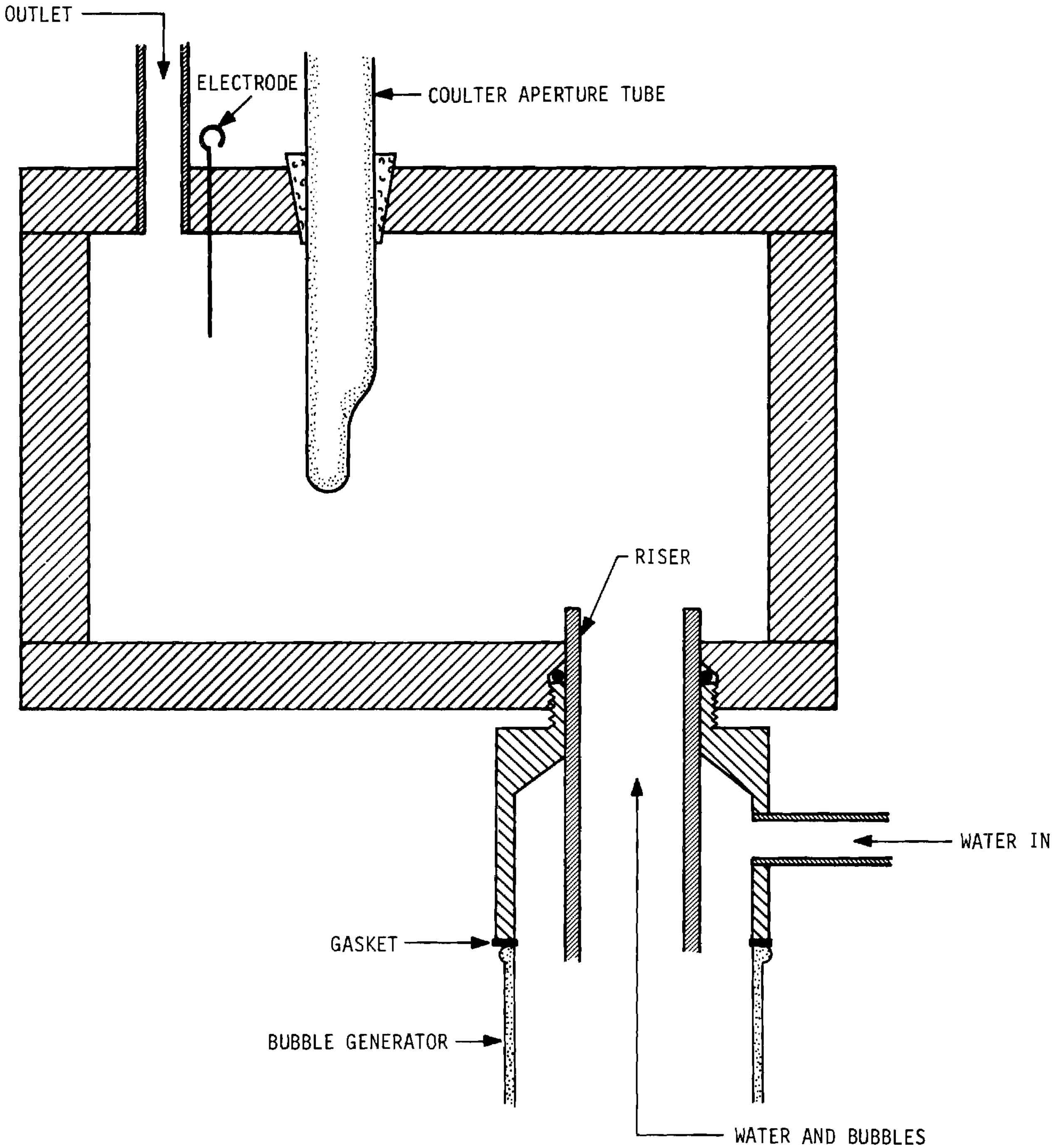

Figure 2. Plenum For Bubble Measurement.

surface of the curved riser extension and are discharged about a centimeter above the counter aperture.

Early measurements were made by forcing synthetic sea water through the bubble generator from one reservoir under air pressure to a vented one. The second design introduced a constant level reservoir 300 cm above the frit. The flow was regulated as desired so that usually the actual head was substantially less. The minimum would be the static head to the overflow, 65 cm. From the overflow, vented to the air, the water entered a flow meter, thence to a 2-liter reservoir which supplied the circulating pump at constant head. A peristaltic pump with adjustable drive operated on the plastic tubing, avoiding contamination. From the pump the water was returned to the upper reservoir. This arrangement provided for continuous operation with two liters of water, important in view of the difficulty in providing a supply of Gulf water.

2. Photographic technique

The plenum, fabricated from 1/2-inch polymethyl methacrylate, was four inches high, six inches long and two inches wide inside. The counter aperture tube, about 7/16-inch in diameter, projected through the top of the plenum. The tube could be aligned so that the aperture plate was parallel to the front side of the plenum, facing the camera. The camera axis was perpendicular to the front of the plenum so that it could be focussed on the aperture plate.

Illumination was provided by two Strobotac 1531A light sources which were mounted to right and left of the plenum, facing each other. Each source was at 90° from the camera axis. The sources were set to single flash, both operated from a push button so that one or a counted number of flashes could be made for each exposure.

The camera was constructed with a Microtessar F/4.5 lens of 48 mm focal length, the shortest which would focus on the aperture, behind 1/2 inch of plastic and nearly 1 inch of water. An EYEMO 35 mm camera, lever-operated to open the shutter for one frame and then advance the film when the shutter was closed, was used. The dimensions were adjusted to give a magnification of eight.

The lighting was chosen to give a highlight on the surface of the bubble from each source so that each bubble would appear as two dots in the correct orientation. The sources should have been at a greater angle from the camera since total reflection from water to air in the bubble occurs at 41.4° and the angle should exceed twice this. Reflection at 90° is 3.8/25.3 or 15% of that at 97.2° between camera and lamp[16]. At an angle greater than 90°, part of the field would have been in the shadow of the aperture plate and tube.

B. Bubble measurements

1. Coulter counter measurements

Each aperture used was calibrated with pollen of suitable size: ragweed, 19 microns; pecan, 48 microns; and corn, 98 microns. Since calibrated pollen was not available, laborious micrometer microscope counts were required. Since no effective means was found to keep the pollen in suspension in the circulating system, the calibration was done on the bench stand, where a stirrer could be used.

The electronics of the Model B counter are overloaded by an excess of particles with a wide range of sizes. With the bench stand, dilution of a suspension decreases the count to a manageable number. In counting bubbles, the count must be reduced to an acceptable level by control of the number of bubbles.

In the early measurements, the usable limit was exceeded. Progressive steps were taken in reducing the area of frit so that the number of bubbles was within acceptable limits with low differential air pressure on the frit. The standard procedure for correction for coincident particles, varying as the square of the count, was used. This correction becomes increasingly uncertain with the concentration of particles.

Measurements of bubbles were corrected for background particulate matter. The samples of Gulf water kindly supplied by the Laboratory varied greatly in the amount of coarse material in suspension. Usually runs could be made with the 100-micron aperture, but the 20-micron aperture clogged repeatedly. This difficulty was avoided by scalping with a 30-micron screen. Bubbles were removed by boiling under vacuum at room temperature.

a. Count analysis. The bubble counts above each diameter, d, indicated by the setting of the counter were reduced to the count in one cm^3, n. The flow discharge from the aperture was measured with a graduate over a long enough time to give a reliable measurement and reduced to the counting time, usually 20.8 seconds. A plot of log n *vs* log d is linear for a log-normal distribution. The plots were generally linear over a range of diameters of about 3 to 1. Counts of large bubbles indicate too short a counting period for statistical reliability. The fall-off in counts for small bubbles is instrumental. The valid range was extended by exchange of the aperture for a smaller one.

From the plot the count of particles smaller than a desired diameter was read, then subtracted from the count for the next larger size, giving the number in that size interval. More than 100 runs were made during the evolution of the equipment. Since each size limit was counted in sequence, a run required twenty minutes or more. Repeat readings indicated that the stability of the system was often less than desired.

2. Photographic bubble measurements

The camera described above was aligned and focussed on the Coulter aperture at F/4.5 then reduced to F/16 to increase the depth of focus. The image of the aperture provided a calibration of the scale of the photograph. The computed depth of focus, confirmed by measurements in air, is 0.1 cm with half this depth in front of the aperture. In water the depth of focus is reduced to 0.05/1.33 or 0.038 cm.

The area photographed, 0.27 x 0.19 cm, with the usable depth of field gives a volume of 1.9×10^{-3} cm^3. Twenty-nine photographs taken during a particular run were exposed to a total of 182 flashes of the strobe light. The volume searched, therefore, is 0.35 cm^3. The bubble diameters, estimated to 1 micron, were sorted in 10-micron intervals as shown in Table I.

Just before the photos were taken, a run with a counter aperture of 560 microns gave the size distribution indicated. When this count is reduced to the same effective volume as used for the photo, it is seen that the photo count confirms the trend, approaching the same count in the range of 50 to 90 microns. The rapidly decreasing photo count at small diameter indicates the difficulty in photographing the highlights since the brightness decreases rapidly with the diameter and the image is lost in the background.

In retrospect, the drawback of the photographic technique is recognized as the decrease in reflected intensity with the second power of the radius of the reflecting sphere, seriously limiting the size range which can be photographed.

TABLE I

Bubble Counts

Photo vs Counter

Size Interval Microns	Size Distribution No. Photo in 0.33 cm^3	No. Counter in 1 cm^3	No. Counter in 0.35 cm^3
30 to 40	4	0	0
40 to 50	12	73	26
50 to 60	10	43	15
60 to 70	0	22	7.7
70 to 80	4	12	4.2
80 to 90	1	7.0	2.4
90 to 100	0	4.0	1.4
100 to 110	0	2.1	0.7

IV. CONCLUSIONS

The work with the Coulter Counter indicates no basic reason to doubt the capability of the instrument to measure bubbles as accurately as particles. Many of the difficulties encountered due to stability of the equipment would be relieved by use of the later models which count a number of size ranges simultaneously. Stoppage of the aperture by large particles can be largely avoided by screening with provision for back flushing.

There appears to be little liklihood that the flow through the aperture appreciably distorts the measured bubble volume. It was noted that millimeter bubbles, although broken up to a cluster of small bubbles on emergence, gave reliably only one count.

The photographic technique, while avoiding many problems of back-lighting, is applicable only over a small size range.

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